Concentrating Photovoltaic Module Testing at NREL's Concentrating Solar Radiation Users Facility

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ABSTRACT

There has been much recent interest in photovoltaic modules designed to operate with concentrated sunlight (>100 suns). Concentrating photovoltaic (CPV) technology offers an exciting new opportunity as a viable alternative to dish Stirling engines. Advantages of CPV include potential for >40% cell efficiency in the long term (25% now), no moving parts, no intervening heat transfer surface, near-ambient temperature operation, no thermal mass, fast response, concentration reduces cost of cells relative to optics, and scalable to a range of sizes.

Over the last few years, we have conducted testing of several CPV modules for DOE's Concentrating Solar Power (CSP) program. The testing facilities are located at the Concentrating Solar Radiation Users Facility (CRULF) and consist the 10 kW High-Flux Solar Furnace (HFSF) and a 14m^2 Concentrating Technologies, LLC (CTEK) dish. This paper will primarily describe the test capabilities; module test results will be detailed in the presentation.

1. General Introduction

Various CPV system configurations are possible. The two most common are reflective dishes with dense-packed arrays and multiple, single cell concentrators (reflective or refractive). Existing examples are the 20-25 kW dish systems designed by Solar Systems, Ltd. of Australia (Fig. 1) and the Amonix 25-35 kW MegaModule™ (Fig. 2). Amonix has installed nearly 500 kW for Arizona Public Service [1]. CSP's support for CPV systems has been exclusively in developing

Figure 1. Solar Systems 20 kW CPV dish prototype.

Figure 2. Amonix 25 kW systems installed in Arizona.

dense-packed arrays or other novel concepts for use with dish concentrators (the PV program has supported other concentrator concepts). One of the primary requirements for dense-packed arrays is uniform flux over areas of series connected cells. Typical dish concentrators for heat engine applications are designed for maximum power through a minimum aperture and therefore the typical designs are not appropriate for CPV systems. Uniform flux is possible either by redesigning the optics of the primary concentrator and/or by adding secondary optical elements to tailor the flux delivered by the primary. We have taken both approaches in our work.

2. Design of Secondary for HFSF Testing

The primary concentrator at the HFSF is designed to deliver 10kW with a Gaussian flux distribution, with peak flux of 250 W/cm^2. In order to "defocus" the primary we aimed the 25 facets at discrete targets, instead of aiming at the same target point. The best results were obtained by spacing the aim points 2.25 cm apart in a rectangular pattern. This aiming strategy was not sufficient to produce a highly uniform flux, therefore a secondary concentrator was designed using SolTRACE [2]. Many configurations were analyzed and a single design was chosen. This secondary had an entrance aperture of 15 x 15 cm and an exit aperture of 8.36 cm x 8.36 cm, the size of the module. The length of

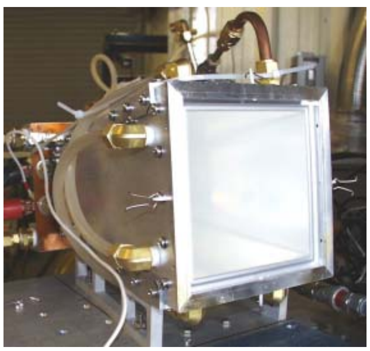

Figure 3. Secondary for use at the HFSF shown with diffuse window in place at entrance aperture.

the secondary was 32.5 cm and consisted of four trapezoidal mirrors (1mm thin silvered glass) with a reflectivity of 0.95. We investigated not only the 2.25 cm spacing, but 0 cm spacing, with all facets pointed at the same target point, representing the nominal Gaussian profile. First the secondary was modeled with no entrance window. The results of the modeling are shown in Figure 4.

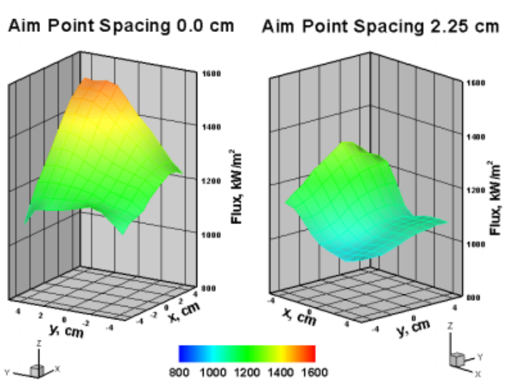

Figure 4. Modeled flux maps using SolTRACE

However, these results did not provide the desired level of uniformity. One method to improve the uniformity is to add a diffusing window. This option was modeled and found to provide excellent results. Figure 5 shows the uniformity with and without a diffusing window.

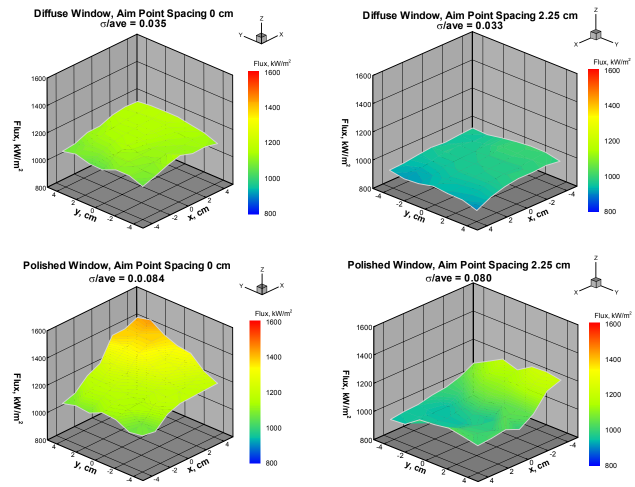

Figure 5. SolTRACE results with diffusing window.

3. CTEK Dish Flux Mapping

This dish, shown in Figure 6, was designed specifically for use with CPV modules. Each of the 16 panels consists of 49 flat mirror tiles, mounted on a spherical substrate. The panels are aligned with a single aim point. A secondary concentrator is needed to smooth the flux to acceptable levels of uniformity. Flux measurements were made using an 8-bit imaging system and software that utilizes a fully diffusing plate as a transmitting target [3]. This allows the camera to be placed behind the exit of the secondary. Flux maps (Figure 7) taken indicate excellent uniformity for this dish system.

Figure 6. CTEK 14 m^2 dish shown without secondary and module.

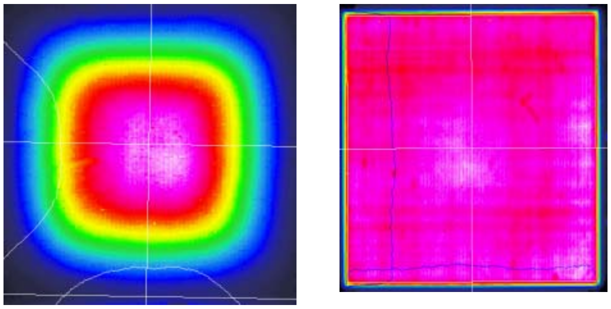

Figure 7. Flux map of CTEK dish secondary entrance and exit planes (not to same scales).

3. Description of Modules Tested

Three separate subcontracted efforts were funded to develop CPV modules. Two were associated with dense-packed arrays and a third was a unique cavity concept. The two dense-packed array efforts were with Amonix and Spectrolab.

Amonix designed, fabricated and tested three modules, two for the HSFS and one for the CTEK dish. Each of these used high efficiency silicon cells. A photo of one of these arrays is shown in Figure 8. Test results were encouraging, but the cooling system developed leaks that prevented extensive testing of any of these modules.

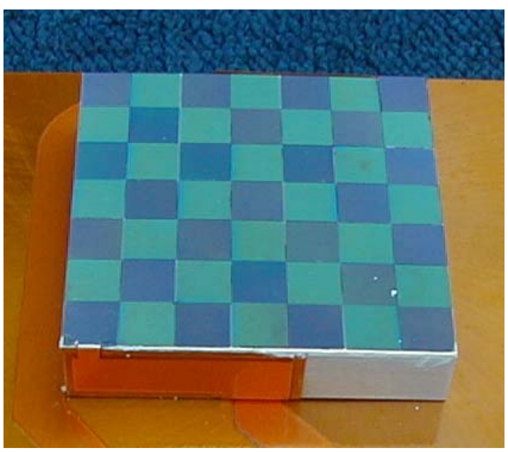

Figure 8. Amonix dense packed array.

Spectrolab designed, fabricated and tested two modules for the HFSF using high efficiency multijunction cells. One of the Spectrolab modules is shown in Figure 9. Test results were very encouraging with cell area based efficiencies over 25%. A low packing factor will need to be improved with these designs and will be the focus of additional effort.

The third module was a cavity design from United Innovations. This concept uses four discrete cell types tiled over the interior of a cooled integrating sphere. Concentrated sunlight is admitted to the sphere through a small entrance at high concentration then diffused throughout the sphere interior resulting in high flux

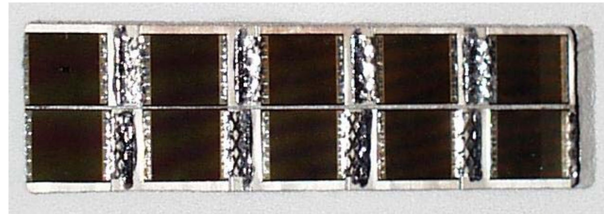

Figure 9. Spectrolab dense-packed module.

uniformity. Unique filters are used on the top of each cell to reject all out of out of bandgap radiation and admit all photons within the bandgap. A schematic of the concept is shown in Figure 10. Testing is currently underway and will be reported at the Review.

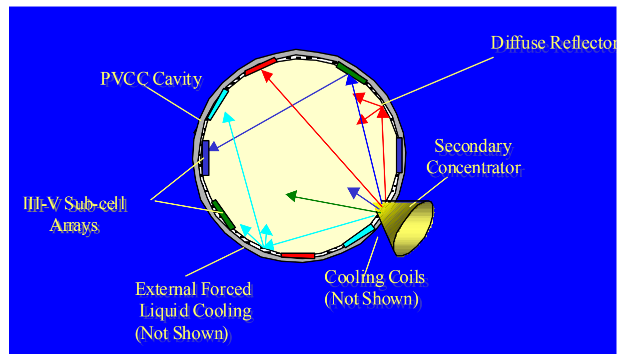

Figure 10. United Innovations photovoltaic cavity converter concept(PVCC).

4. Conclusions

A unique and versatile test facility for testing CPV modules exists at the CSRUF and has been used to evalulate a number of industry-designed concepts. The ability to provide uniform flux and control flux levels using the HFSF offers a full range of characterization possibilities for modules in the output range up to 2 kW and at flux levels exceeding 100 W/.cm^2. Larger-scale testing and longer-term reliability and durability testing is possible using the CTEK dish

References

[1] Kenneth W. Stone, Vahan Garboushian, David Roubideaux, Robert Gorden, Jerry Turner, David Dutra, Design & Performance of the Amonix High Concentration Solar PV System, ASES/ASME National Solar Energy Conference, Reno NV, June 15-20, 2002

[2] Wendelin, Tim, SOLTRACE User Manual; to be presented at 2003 ASME International Solar Energy Conference, March 2003.

[3] Lewandowski, A., C. Bingham, A. Neumann, “Flux Mapping Using Transmitting Lambertian Targets”, 1999 ASME International Solar Energy Conference, April 11-15, 1999, Lahaina, HI.